Improved spin basis for angular correlation studies in single top quark production at the Fermilab Tevatron

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We show in single top quark production that the spin of the top quark is correlated with the direction of the d-type quark in the event. For single top-quark production in the W^* channel, the d-type quark comes dominantly from the antiproton at the Fermilab Tevatron, whereas for the W-gluon fusion channel the spectator jet is the d-type quark the majority of the time at this machine. Our results are that 98% of the top quarks from the W^* process have their spins in the antiproton direction, and 96% of the top quarks in the W-gluon fusion process have their spins in the spectator jet direction. We also compare with the more traditional, but less effective, helicity basis. The direction of the top quark spin is reflected in angular correlations in its decay products. [S0556-2821(97)01711-6]

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I. INTRODUCTION

The single top quark production processes are of great importance at hadron colliders since they allow a direct measurement of the coupling of the W boson to the top quark, i.e., the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{tb}|$. These processes can also be used to search for anomalous couplings of the top quark. With a mass in the neighborhood of 175 GeV [1], the top quark is by far the heaviest of the known quarks. As a consequence, the electroweak decay of the top quark proceeds so rapidly that top quarkonium-bound states and T mesons do not have time to form [2] and the decay products of the top quark are correlated with its spin [3]. Therefore, if a top quark is produced with a significant spin correlation, this correlation will be translated into large angular correlations in such events. Studies of these angular correlations in single top quark production can then be used as sensitive searches for anomalous couplings of the top quark, i.e., physics beyond the standard model [4–7].

Traditionally, in high-energy physics processes, the discussions of spin-related observables take place in terms of the helicities of the fermions involved. However, this description is most useful when the fermions are produced in the ultrarelativistic limit because in this limit the chirality eigenstates are identical to the helicity eigenstates. For fermions which are not ultrarelativistic, such as the top quarks produced at the Fermilab Tevatron, one must deal with the fact that the chirality and helicity of a massive fermion may not be specified simultaneously. Therefore, there is no *a priori* reason to believe that the helicity basis will give the best description of the spin of top quarks at the Tevatron. In fact, it has recently been shown that the helicity basis does not lead to the largest values for various spin-related correlations in $t\bar{t}$ production at either the Tevatron [8] or an e^+e^- collider [9]. Thus, it is natural to ask: is there a better spin basis than helicity for the description of the spin correlations in *single* top quark production? The answer to this question is yes: we will construct such a spin basis in this paper.

We will concentrate on two important production mechanisms for single top quarks at the Tevatron. Both of these mechanisms produce the single top quark in a left-handed chirality state through a virtual W boson. Therefore, significant spin correlations are expected even at the Tevatron, where the top quark is produced well below the ultrarelativistic limit. The first of these (Fig. 1) is the purely electroweak W^* channel [10–12]

$$u\bar{d}\to t\bar{b}, \tag{1}$$

while the second (Fig. 2) consists of the so-called W-gluon fusion (Wg fusion) processes [13–19]

$$ug\to tb\bar{d},$$

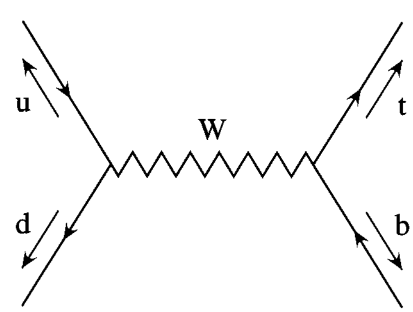

FIG. 1. Feynman diagram for single top quark production in the W^* process. The labels indicate the momentum flow utilized in the text.

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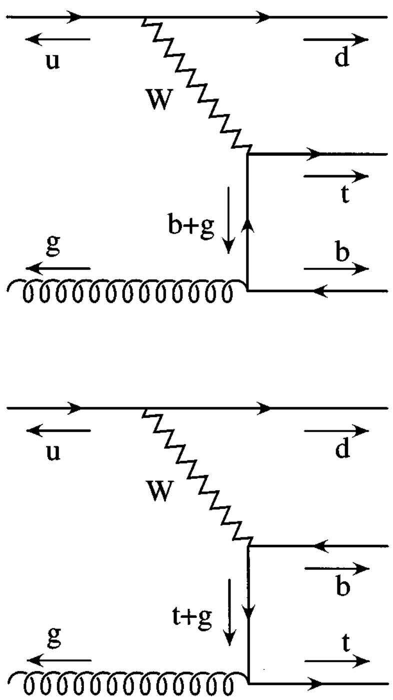

FIG. 2. Gauge-invariant set of Feynman diagrams for single top quark production via Wg fusion. The labels indicate the momentum flow utilized in the text.

$$\overline{d}g \to t\overline{b}\overline{u}. \tag{2}$$

The feasiblity of isolating single top quark production in a collider environment has already been demonstrated for both the W^* channel [11,20] and the W-gluon fusion process [19].

Early on it was recognized by Willenbrock and Dicus [14] that the Wg fusion process is dominated by the configuration where the b quark is nearly collinear with the incoming gluon, leading to a logarithmic factor $\ln(m_t^2/m_b^2)$ in the total cross section. In the event that this factor is too large[1] the perturbative calculation of the $2\to 3$ process becomes unreliable, and one should instead compute $ub\to td$, with the large logarithm being absorbed into the b parton distribution function. This latter approach has been employed by Bordes and collaborators [21–23] in their effort to accurately compute the total cross section, including higher-order corrections. Among their conclusions is the statement that to lowest order, for top quark masses up to a few hundred GeV, the two pictures give comparable event descriptions and lead to similar cross sections [23]. This statement is also true for the top quark spin correlation. Therefore, we will frame our discussion of Wg fusion in terms of the tree-level description involving only the diagrams in Fig. 2.

In Secs. II and III we discuss in detail the top quark spin correlations in single top quark production via the W^* process and Wg fusion process, respectively. Finally, we end with a discussion and conclusions. In the Appendix we give an example in detail of how the top quark spin correlations lead to angular correlations in events. The example given is single top quark production in the W^* channel. Throughout this paper we will only consider processes which produce a top quark in the final state. The treatment of the charge-conjugated processes, where a top antiquark is produced, is similar.

II. SINGLE TOP QUARK PRODUCTION THROUGH A W^*

We begin with the simpler of the two production mechanisms for single top quarks at the Tevatron, the electroweak process $u\overline{d}\to t\overline{b}$, which proceeds via a virtual W boson (see Fig. 1). We represent the momentum of the each particle by its symbol, and write the amplitude in crossing symmetric form with all momenta outgoing. Our results are easily derived using the spinor helicity method for massive fermions described in [8] to treat the top quark spin. In particular, we decompose the top quark momentum into a sum of two massless auxiliary momenta:

$$t_1 \equiv \tfrac{1}{2}(t+m_t s), \quad t_2 \equiv \tfrac{1}{2}(t-m_t s), \tag{3}$$

where s is the usual spin vector of the top quark. In the rest frame of the top quark, the spin of the top quark is in the same direction as the spatial part of t_1. Then, the matrix element squared for the production of a spin-up top quark summed over color and all of the other spins[2] is

$$|\mathcal{M}(0\to\overline{u}dt_\uparrow\overline{b})|^2 = g_W^4|V_{ud}|^2N_c^2\frac{(2d\cdot t_2)(2u\cdot b)}{(2u\cdot d-m_W^2)^2+(m_W\Gamma_W)^2}, \tag{4}$$

while for a spin-down top quark we have

$$|\mathcal{M}(0\to\overline{u}dt_\downarrow\overline{b})|^2 = g_W^4|V_{ud}|^2N_c^2\frac{(2d\cdot t_1)(2u\cdot b)}{(2u\cdot d-m_W^2)^2+(m_W\Gamma_W)^2}, \tag{5}$$

where g_W is the weak coupling constant, m_W and Γ_W are the mass and width of the W boson, N_c is the number of colors, and V_{ud} is the Cabibbo-Kobayashi-Maskawa matrix element. Throughout this paper we assume the standard model with three generations and suppress the CKM factor $|V_{tb}|^2\approx 1$. The sum of Eqs. (4) and (5) is obviously independent of the choice of the spin axis of the top quark, as is required.

It is clear that the top quarks produced via the W^* process are 100% polarized along the direction of the d-type quark, since Eq. (5) vanishes if we choose $t_1 \propto d$. Consequently, the ideal basis for studying the t spin is the one which uses the direction of the d-type quark as the spin axis. (See the Appendix for a discussion of this process keeping track of all of

[1]The authors of Ref. [14] suggest $(g_s^2/4\pi^2)\ln(m_t^2/m_b^2)\approx 0.23$ as a suitable measure, where g_s is the strong coupling constant, the top quark mass $m_t = 175$ GeV, and the bottom quark mass $m_b = 5$ GeV.

[2]Although we have summed over the spins and colors of the initial particles, we have not performed the spin or color average in any of the matrix elements appearing in this paper.

TABLE I. Fractional cross sections for single top quark production in the W^* channel at the Tevatron at 2.0 TeV, decomposed according to the parton content of the initial state. We use the Martin-Roberts-Stirling set R1 [MRS(R1)] structure functions [25] evaluated at the scale $Q^2 = m_W^2$. We obtain a total cross section of approximately 0.33 pb.

p	$\bar{p}$	Fraction
u	$\bar{d}$	98%
$\bar{d}$	u	2%

the correlations between production and decay.) Of course, in an actual experiment, we know only that one of the two initial state partons is a $\bar{d}$. However, the largest contribution to the total cross section comes from the case where the $\bar{d}$ is donated by the antiproton. In fact, for the Tevatron at 2 TeV, we estimate that 98% of the cross section may be attributed to this configuration (see Table I). This suggests that an excellent choice would be to decompose the top quark spin along the direction of the antiproton beam, independent of the actual identity of the parton supplied by that beam. We will refer to this choice as the ''antiproton'' basis.

To aid in the comparison of the antiproton basis to the more traditional helicity decomposition, we present the matrix elements as a function of the angle θ^* between the direction of the top quark in the zero-momentum frame (ZMF) of the initial parton pair and the $+z$ axis, and the speed β of the top quark in the ZMF. We orient our coordinate system such that the protons travel in the positive z direction; the antiprotons travel in the negative z direction. Because Eqs. (4) and (5) are not symmetric under the interchange of u and $\bar{d}$, the expressions we obtain in terms of these variables will depend upon which beam the $\bar{d}$ quark comes from. In the following equations, the parton taken from the proton will always be written first, followed by the parton taken from the antiproton.

We now turn to the actual matrix elements for the antiproton basis, where spin up means that in the rest frame of the top quark, its spin points in the same direction as the incoming antiproton beam is traveling in that frame. For the 98% of the time that the $\bar{d}$ comes from the antiproton, we have

$$|\mathcal{M}(u\bar{d}\to t_\uparrow\bar{b})|^2 = \frac{g_W^4|V_{ud}|^2N_c^2}{\mathcal{W}}\beta(1+\cos\theta^*)(1+\beta\cos\theta^*), \tag{6}$$

where

$$\mathcal{W} \equiv [(1-\xi)+\beta(1+\xi)]^2 + \left[\xi(1-\beta)\frac{\Gamma_W}{m_W}\right]^2 \tag{7}$$

and $\xi \equiv m_W^2/m_t^2$. The spin-down amplitude vanishes in this case. On the other hand, when the $\bar{d}$ is supplied by the proton instead, we obtain

TABLE II. Dominant spin fractions and asymmetries for the various bases studied for single top quark production in the W^* channel at the Tevatron at 2.0 TeV.

Basis	Spin content	$\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$
Helicity	83% $\downarrow$(L)	-0.66
Proton	83% $\downarrow$	-0.67
Antiproton	98% $\uparrow$	0.96

$$|\mathcal{M}(\bar{d}u\to t_\uparrow\bar{b})|^2 = \frac{g_W^4|V_{ud}|^2N_c^2}{\mathcal{W}}\frac{\beta^3(1-\cos^2\theta^*)(1-\cos\theta^*)}{1+\beta\cos\theta^*} \tag{8}$$

for spin up, and

$$|\mathcal{M}(\bar{d}u\to t_\downarrow\bar{b})|^2 = \frac{g_W^4|V_{ud}|^2N_c^2}{\mathcal{W}}\frac{\beta(1-\beta^2)(1-\cos\theta^*)}{1+\beta\cos\theta^*} \tag{9}$$

for spin down. Thus, the presence of a $\bar{d}$ sea in the proton introduces a small quantity of spin-down top quarks into the sample. Indeed, this contribution is dominated by the spin-down component. However, the smallness of this contribution still results in a sample in which the top quark spin is aligned with the antiproton direction in the top quark rest frame 98% of the time.

We now compare these results to the helicity basis, using the ZMF as the frame in which we measure the helicity. We begin with the case where the $\bar{d}$ quark comes from the antiproton, for which the matrix element squared is

$$|\mathcal{M}(u\bar{d}\to t_\uparrow\bar{b})|^2 = \frac{1}{2}\frac{g_W^4|V_{ud}|^2N_c^2}{\mathcal{W}}\beta(1-\beta)(1-\cos^2\theta^*) \tag{10}$$

for the production of spin-up (right-handed helicity) top quarks and

$$|\mathcal{M}(u\bar{d}\to t_\downarrow\bar{b})|^2 = \frac{1}{2}\frac{g_W^4|V_{ud}|^2N_c^2}{\mathcal{W}}\beta(1+\beta)(1+\cos\theta^*)^2 \tag{11}$$

for the production of spin-down top quarks. The expressions for the $\bar{d}u$ intial state may be obtained by making the replacement $\cos\theta^* \to -\cos\theta^*$. The spin-up amplitude is proportional to $1-\beta$, causing it to vanish in the ultrarelativistic limit. At more moderate values of β, such as are dominant at the Tevatron, both spins are produced, with spin-down (left-handed helicity) top quarks predominating. We find that in the overall mixture at the Tevatron, 83% of the top quarks have left-handed helicity.

Table II summarizes the purities for the helicity, antiproton, and for completeness, proton bases. The proton basis is

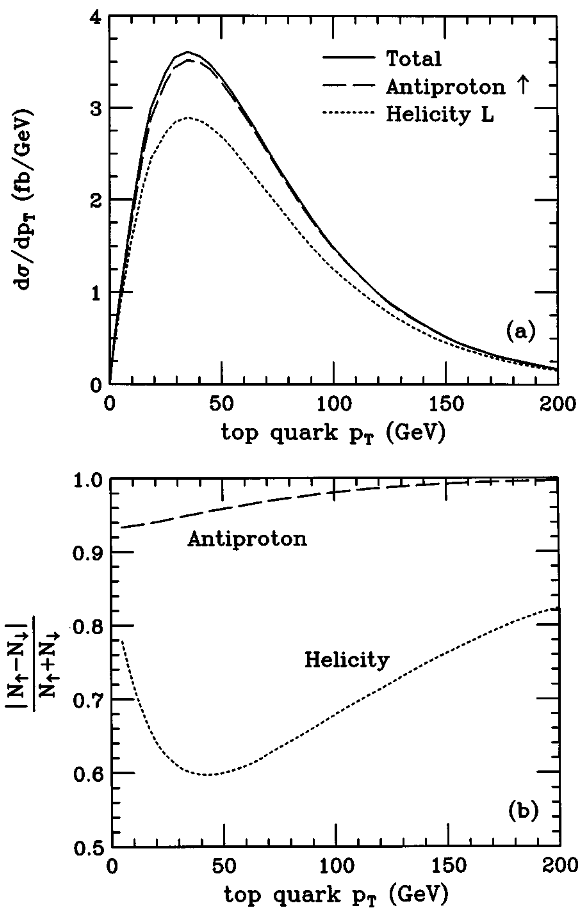

FIG. 3. (a) The differential cross sections (total, antiproton basis spin up, helicity basis left) as a function of the top quark transverse momentum for single top quark production in the W^* channel at the Tevatron at 2.0 TeV. (b) The absolute value of the spin asymmetry (12) plotted as a function of the top quark transverse momentum for the helicity and antiproton bases.

defined by choosing $t_1 \propto p$, i.e., the parton donated by the proton beam.[3] Also included are the values of the spin asymmetries

$$\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \tag{12}$$

for each basis, as this is the coefficient which determines the magnitudes of the angular correlations. Thus, the improvement from 83% left-handed helicity to 98% spin up in the antiproton basis translates into a factor of 1.45 increase in the size of the correlations. We plot the differential distributions in top quark p_T for the helicity and antiproton bases as well as the total in Fig. 3.

TABLE III. Fractional cross sections for single top quark production in the Wg fusion channel at the Tevatron at 2.0 TeV, decomposed according to the parton content of the initial state. We use the MRS(R1) structure functions [25] evaluated at the scale $Q^2 = m_W^2$. We obtain a total cross section of approximately 0.47 pb.

p	$\bar{p}$	Fraction
u	g	74%
g	$\bar{d}$	20%
g	u	3%
$\bar{d}$	g	3%

III. W-GLUON FUSION

The dominant production mechanism for single 175 GeV top quarks at the Tevatron is the so-called Wg fusion process. We consider the processes (2) and hence the gauge-invariant set of diagrams shown in Fig. 2. Once again, we use the symbol for each particle to represent its momentum. For convenience, we employ the explicitly crossing-symmetric form in which all momenta are outgoing. Because Wg fusion is a $2 \to 3$ process, the polarized production matrix elements squared for an arbitrary spin axis are too complicated to reproduce here [24]. However, the sum over all spins and colors may be simply written as[4]

$$|\mathcal{M}(0 \to \overline{u}\overline{d}gt\overline{b})|^2 = \frac{g_W^4 g_s^2 |V_{ud}|^2 N_c (N_c^2 - 1)}{(2u\cdot d - m_W^2)^2} \times |\mathcal{Z}(u,d;t,b) + \mathcal{Z}(d,u;b,t)|, \tag{13}$$

where

$$\mathcal{Z}(u,d;t,b) = (2d\cdot t)\left\{ \frac{t\cdot u}{t\cdot g} - \frac{u\cdot(b+g)}{b\cdot g}\left[1 - \frac{b^2}{b\cdot g} + \frac{t\cdot b}{t\cdot g}\right]\right\}. \tag{14}$$

We present the relative contributions to the cross section from each of the partonic initial states for this process in Table III. As expected from the observation that the proton contains two u quarks while the antiproton contains only one $\bar{d}$ quark, the ug initial state gives the largest contribution (74%) to the total. In terms of the helicity basis (defined in the zero-momentum frame of the incoming partons), we find that approximately 83% of the top quarks have negative helicity (see Table IV), leaving significant room for improvement.

To illuminate our improved basis, we present the matrix element squared for the production of spin-down top quarks in the basis where the spin axis is chosen to coincide with the d-quark direction:

[3]The analytic forms of the matrix elements squared in the proton basis are easily obtained: Eqs. (8) and (9) apply to the ud initial state once the replacement $\cos\theta^* \to -\cos\theta^*$ is made. Likewise, Eq. (6) represents the lone nonvanishing contribution from the du initial state after making the same replacement.

[4]When the initial state partons are chosen such that the W momentum is timelike, one should add the standard width term to the W propagator.

TABLE IV. Dominant spin fractions and asymmetries for the various bases studied for single top quark production in the Wg fusion channel at the Tevatron at 2.0 TeV.

Basis	Spin content	$\dfrac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$
Helicity	83% $\downarrow$(L)	-0.67
Proton	68% $\uparrow$	0.37
Antiproton	54% $\downarrow$	-0.07
Spectator	96% $\uparrow$	0.91

$$|\mathcal{M}(0\to\overline{u}\overline{d}gt_\downarrow\overline{b})|^2 = \frac{g_W^4 g_s^2 |V_{ud}|^2 N_c(N_c^2-1)}{(2u\cdot d - m_W^2)^2}\,\frac{m_t^2(g\cdot d)^2}{(t\cdot g)^2}\left|\frac{u\cdot b}{t\cdot d}\right|. \tag{15}$$

Besides being surprisingly simple, this result is significant in that it comes exclusively from the lower diagram in Fig. 2; hence, there are no inverse powers of $2b\cdot g$ from the b-quark propagator. As is well known [14], in the limit of vanishing b-quark mass, the Wg fusion process develops a collinear singularity. For the physical (nonzero) value of the b mass, this is reflected in the tendency for the b quark to be produced at large pseudorapidity. Thus, the majority of the total rate comes from the regions of phase space where $2b\cdot g$ is small: hence the spin-down component (no pole in $2b\cdot g$) is suppressed relative to the spin-up component. In fact, for the ug and gu partonic initial states, we find that 97% of the top quarks are produced with spin up in this basis.

Since for the ug and gu initial states the d quark becomes the spectator jet, we define the ''spectator'' basis by electing to use the direction of the spectator jet (defined as the light jet appearing in the $\ell\nu bbj$ final state) for the spin axis. Although this picks the wrong spin axis direction for the gd and dg initial states, it is correct the majority of the time. We find that the overall composition consists of 96% spin-up top quarks in this basis. For comparison, we give the results for the proton and antiproton bases in Table IV. In terms of the spin asymmetry defined in Eq. (12), we see that the spectator basis represents a factor of 1.36 improvement over the helicity basis. The differential distributions in top quark p_T for the helicity and antiproton bases as well as the total appear in Fig. 4.

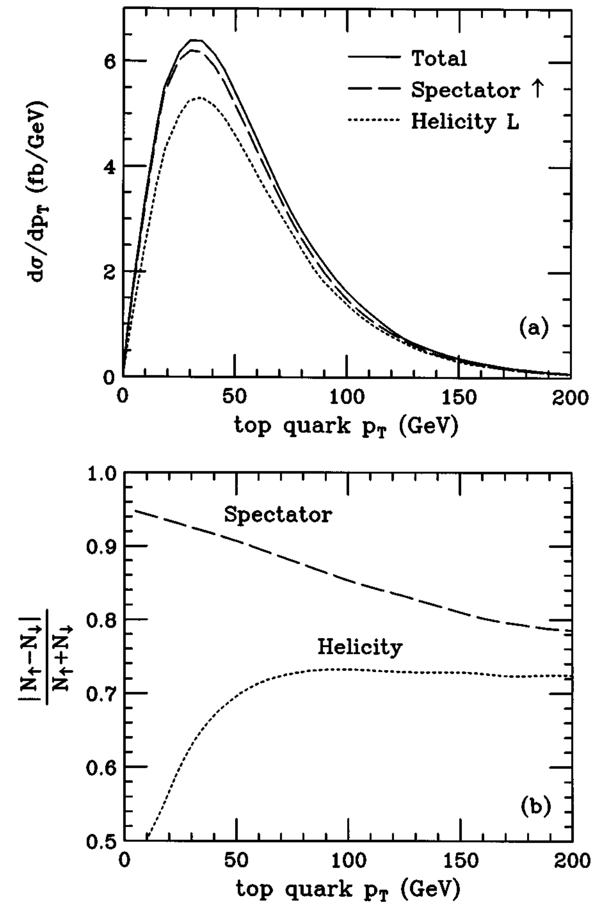

FIG. 4. (a) The differential cross sections (total, spectator basis spin up, helicity basis left) as a function of the top quark transverse momentum for single top quark production via Wg fusion at the Tevatron at 2.0 TeV. (b) The absolute value of the spin asymmetry (12) plotted as a function of the top quark transverse momentum for the helicity and spectator bases.

IV. DISCUSSION AND CONCLUSIONS

In this paper we have found that the direction of the d-type quark provides the most effective spin axis for all single top quark production mechanisms. However, experimentally we do not know with certainty which physical object comprises the d-type quark in a given event. We have chosen the object which is most likely to be the d-type quark. In the case of the W^* production mechanism, this means the direction of the antiproton beam, since it supplies the $\bar{d}$ quark 98% of the time at the Tevatron. Using the antiproton as our basis, we find that the top quark is 98% spin up. As a result, the angular correlations with this choice of spin axis are 45% larger than those using the helicity basis.

For Wg fusion, the situation is potentially more complicated. Nearly three-quarters of the cross section comes from the situation where the proton donates a u quark: hence the d quark appears as the spectator jet in the final state. In double-tagged events, identifying this jet is trivial; in other cases, it may be necessary to assume that the jet with the largest pseudorapidity is the spectator jet. Although a full simulation is beyond the scope of this paper, it is clear that this identification can be achieved with a small error rate because of the unique kinematics of this process. Using the spectator jet as our basis, we find that the top quark is 95% spin up and that the angular correlations are 36% larger than the correlations using the helicity basis.

We have demonstrated that the helicity basis is *not* the optimal basis for the discussion of angular correlations in single top quark production at the Tevatron. Instead, we have shown that the direction of the d-type quark provides a superior spin axis for *all* single top quark production mechanisms.

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APPENDIX: ANGULAR CORRELATIONS IN $u\overline{d}\to t\overline{b}\to \overline{\ell}\nu b\overline{b}$

For the W^* production process of single top quarks it is instructive to study the full matrix element including both the production and decay of the the top quarks to see how the top quark spin correlation translates into angular correlations in the events. Consider the production of a top quark via

$$u\overline{d}\to t\overline{b} \tag{A1}$$

and its subsequent semileptonic decay

$$t\to \overline{\ell}\nu b. \tag{A2}$$

Using the symbol of the particle to represent its momentum, the full matrix element squared for this process including all correlations between production and decay, summed over all colors and spins, is given by

$$\begin{aligned}|\mathcal{M}(u\overline{d}\to t\overline{b}\to \overline{\ell}\nu b\overline{b})|^2 &= 2N_c^2 g_W^8 |V_{ud}|^2 (2u\cdot\overline{b})(2b\cdot\nu)\{2(t\cdot\overline{d})(t\cdot\overline{\ell}) - t^2(\overline{d\cdot\ell})\}\\ &\times[(2u\cdot d - m_W^2)^2 + (m_W\Gamma_W)^2]^{-1}\\ &\times[(t^2-m_t^2)^2+(m_t\Gamma_t)^2]^{-1}\\ &\times[(2\overline{\ell}\cdot\nu - m_W^2)^2+(m_W\Gamma_W)^2]^{-1}.\end{aligned} \tag{A3}$$

If we use the narrow-width approximation for the top quark, then the quantity in the curly brackets in Eq. (A3) evaluated in the top quark rest frame is equal to

$$m_t^2 E_{\overline{d}} E_{\overline{\ell}} (1+\cos\theta_{\overline{d}\overline{\ell}}), \tag{A4}$$

where E_i is the energy of the ith particle and $\theta_{\overline{d}\overline{\ell}}$ is the angle between the $\overline{d}$ quark and the charged lepton in this frame. The $(1+\cos\theta_{\overline{d}\overline{\ell}})$ is precisely the correlation expected if the top quark spin is along the direction of the $\overline{d}$-quark momentum in the top quark rest frame. This is confirmation of Eqs. (4) and (5) and discussion that follows in Sec. II.

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